ELECTRIC FIELD PROFILE IN μc-Si:H p-i-n DEVICES

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ABSTRACT

Solar cells based on microcrystalline silicon (μc-Si:H) have demonstrated remarkable efficiencies and have been successfully incorporated in tandem structures; however, little work has so far been devoted to the understanding of these devices. The objective of this paper is to obtain more insight into their physical functioning by extensive characterisation of μc-Si:H devices. Charge-collection experiments shows that high electric field E(x) is present throughout the entire i-layer of thick p-i-n device. Furthermore, from capacitance studies, one concludes that the electric field profile is partly concentrated at grain boundaries. In contrast with these two observations, spectral response under forward bias voltage show that thick μc-Si:H p-i-n devices are (unlike a-Si:H p-i-n devices) not fully field-controlled.

INTRODUCTION

Recent progress has demonstrated that microcrystalline hydrogenated silicon (μc-Si:H) is a very attractive material for the active layer of thin film solar cells. Efficiencies of up to 8.3 % have been demonstrated on entirely microcrystalline p-i-n cells with no sign of light-induced degradation [1, 2, 3]. Due to the lower absorption coefficient of μc-Si:H for visible light (as compared to a-Si:H), this material requires relatively thick solar cell (the i-layer thickness is usually between 2 and 5 μm) in order to absorb the useful part of the solar spectrum.

Charge-collection experiments (TOF - Time of Flight) on thick p-i-n devices have shown that collection is usually almost complete even without applying an external bias voltage (i.e. in short-circuit conditions), confirming the presence of a relatively high and constant internal field within the i-layer. Indeed, this fact suggests at first sight (by comparison with a-Si:H p-i-n devices) that transport in μc-Si:H cells may also be field controlled. On the other hand, from spectral response measurements (SR) and current-voltage (IV) characteristics, it was originally deduced that diffusion plays an important role in the charge collection for these "thick" devices, when they are operated close to the maximum power point [4]. C(V) measurements also showed that the capacitance of μc-Si:H devices can be much higher that the geometrical capacitance [5, 6]. This means that the electric field is in fact concentrated in specific region of the i-layer.

The goal of this work is to combine charge collection, capacitance, spectral response and current-voltage measurements in order to clarify both the electric field distribution and transport mechanisms in μc-Si:H p-i-n devices.

EXPERIMENT

All μc-Si:H samples were grown by the VHF-GD deposition technique at frequencies between 70 and 130 MHz, in a capacitively-coupled parallel-plate reactor. Typical deposition conditions may be found in Refs. 1 and 7. P-i-n and n-i-p cells were deposited on TCO-coated glass substrates (Asahi type U) and terminated either with a ZnO or ITO top or back contact, in order to provide a transparent contact on both sides for charge collection evaluations. Furthermore, two pairs of comparable p-i-n cells of different thicknesses were also deposited in the same run by shielding a part of the substrate (during i-layer deposition) behind a shutter, in order to obtain diodes with two different intrinsic layer thicknesses. A series of μc-Si:H samples was also deposited at variable plasma power (at a fixed excitation frequency of 130 MHz and fixed dilution of 7.5% of silane in hydrogen), in order to get materials with varying crystalline content.

Current vs. voltage characteristics were measured on p-i-n structures with a back TCO/Ag contact in the dark and under AM1.5 conditions at 100 mW/cm^{-2} using a two-source solar simulator (Wacom WXS-140S-10). Capacitance measurements were performed either with an HP4192 impedance analyser or with a Quadtech 7500 LCR meter.

Electric Field Determination

To determine electric field profiles E(x) in p-i-n solar cells, two methods based on the TOF technique are available. The first one introduced by Street [8] relies on the current transient of a drifting sheet of charges. Beside the fact that this method has generally a poor spatial resolution (at least with standard TOF equipment), it is in most cases unsuitable for μc-Si:H. The high capacitance observed in μc-Si:H [5, 6] induces in fact a rather high RC-time constant which tends to distort the current transient.

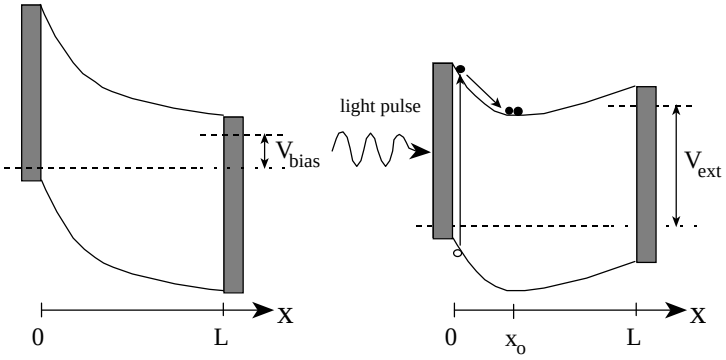

Figure 1: Determination of the electric field profile E(x) according to Vanderhaghen et al. [9]: Cell under bias voltage V_{bias} (usually equal to 0 V) before probing of the internal field (left) and during measurement (right). Zero field location is created at position x_o where the photogenerated carriers, which have drifted from the front contact, accumulate.

The second, method which avoids the drawback of the Street's technique, has been proposed by Vanderhaghen et al. [9]. It relies only on charge collection and does not require knowledge of the exact shape of the measured transients. This method consists of a modified TOF experiment, where an external electric field (pulsed, as in the standard TOF system) is superimposed on the internal field. The aim is to create a zero field location at position x_o in the i layer (cf. Figure 1), where the internal field $E(x_o)$ is cancelled by the externally applied field E_{ext}. By varying this external (forward) polarisation, one can change the position x_o and, thus, probe the field profile E(x). The position x_o (where the internal field $E(x_o)$ is equal to E_{ext}) is then given by the relation

$$Q = Q_0 \frac{x_0}{L} \qquad (1)$$

where L is the sample thickness and Q_0 the total photogenerated charge (which can be determined by measuring the collection under high reverse polarisation).

As a matter of fact, this method is "just" a reinterpretation of the charge collection curve, in terms of internal field distribution. As shown in previous papers of our group [10, 11], the performance of this technique can be decisively improved if one analyses the collection for both types of carriers (a semi-transparent contact must be provided for this purpose on both sides of the sample). A comprehensive discussion of this "bifacial" method may be found in Ref. [11]. As concerns the limits of this technique, two important points must be pointed out. First, the spatial resolution of the technique is limited by the charge generation gradient (i.e. by the penetration depth of the absorbed light). As a consequence, field values close to the p-i interface (or to the n-i interface) tend to be underestimated. All measurements presented in this paper were performed with an excitation light wavelength of 480 nm, giving an penetration depth of roughly 0.2 μm in μc-Si:H and 0.02 μm in a-Si:H. Second, in order to obtain accumulation of charge (so as to create a minimum in the potential profile), the derivative of the field must be opposite to the sign of the charge. This means that "spikes" in the potential profile (i.e. field concentration) that may be present in certain regions of the i-layer are not observed with this technique. As a consequence, built-in voltage values extracted with this method tend to be underestimated.

RESULTS

Electric field profiles measured on a-Si:H and μc-Si:H thick p-i-n cells (> 2 μm) differ quite significantly. As one can see in Fig. 2,the electric field is much more concentrated at the p-i interface in the case of a-Si:H diode (a similar picture is found for the n-i interface), whereas higher field values are found in the centre of the i-layer in the case of μc-Si:H, resulting in a more uniform field profile. Looking at the complete field profile E(x) across the whole i-layer of the p-i-n μc-Si:H cells, one can observe that the field distribution is relatively symmetrical between the p and the n side (see Fig. 3), and scales with the i-layer thickness; by simply integrating E(x) over the whole i-layer one obtains a built-in voltage of ≈0.5 V for both samples plotted in Fig. 3. However, this value seems far too low to reflect its true value. In fact, electric field concentration at interfaces and grain-boundaries, which cannot be seen with the technique used (see remarks in the experimental part), may contribute for a significant part of the built-in voltage. Such a conclusion is further sustained by the increase capacitance observed in μc-Si:H samples (as compared to a-Si:H). Fig. 4 shows the results of capacitance measurements on a

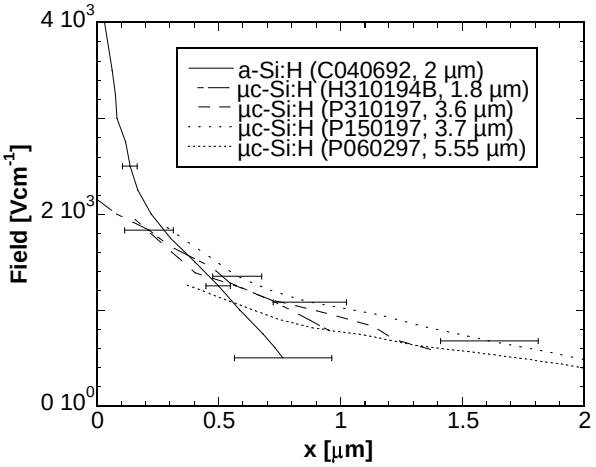

Figure 2: Internal electric field profile E(x) in thick p-i-n (C040692 and H310194B) and n-i-p μc-Si:H solar cells (field profile of a thick a-Si:H p-i-n cell is given for comparison).

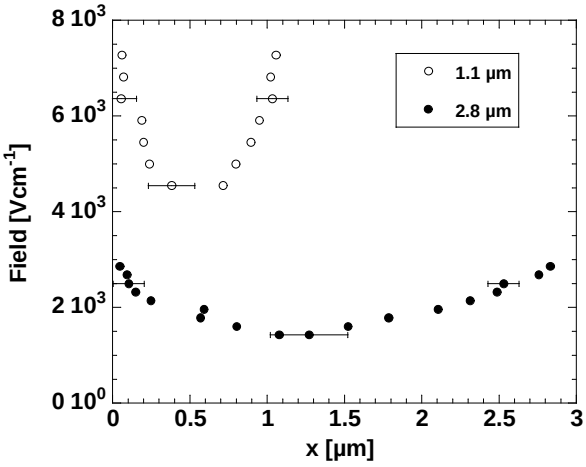

Figure 3: Internal electric field profile in a set of 2 μc-Si:H p-i-n diodes with similar i-layer material but different thicknesses (deposited in the same run).

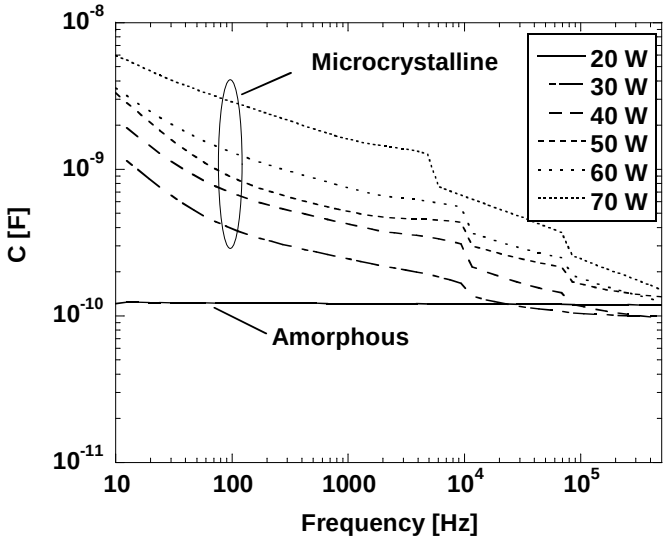

Figure 4: Capacitance as a function of frequency for a series of layers deposited at various deposition power and at 7.5% dilution of silane in hydrogen. The sample deposited at 20 W is amorphous while samples deposited at higher power are microcrystalline. Thickness of all samples were around 2 μm.

power series of μc-Si:H layers: one observes here a marked increase of capacity at frequencies up to 100 KHz as one increases the crystalline content of the sample (the deposition power was used here to scan the transition from amorphous to microcrystalline silicon). Note that the effective permeability $\varepsilon_{eff} = Cd\varepsilon_o / S$ (where C is the capacity, d the thickness and *S* the sample area) approaches the value of 11 (typical for Si) at high frequency, as already observed by Fejfar et al. [6].

At this point, one would like to know where the electric field is concentrated within the i-layer. Capacitance measurements on thickness series are in this context very instructive. In Fig. 5, capacitance measurements of two thickness pairs of μc-Si:H p-i-n cells is plotted. One can observe that for all applied voltages, the measured capacitance is always several time larger than the geometrical one. Furthermore, in both cases, the capacitance scales well with the sample thickness.

In c-Si, a voltage dependance of the capacitance is observed for the depletion region of one-sided abrupt junction which follows the following dependency [12]:

$$\frac{1}{C^2} = \frac{2\left(V_{bi} - V_{app}\right)}{e\varepsilon N_D} \qquad (2)$$

where N_D is the doping level and V_{bi} the built-in voltage. As seen in Fig. 6, for each pair of samples, we obtain a linear dependency between $1/C^2$ and the applied voltage and the slope scales with the sample thickness. However, in our case, we do not have a abrupt junction, but

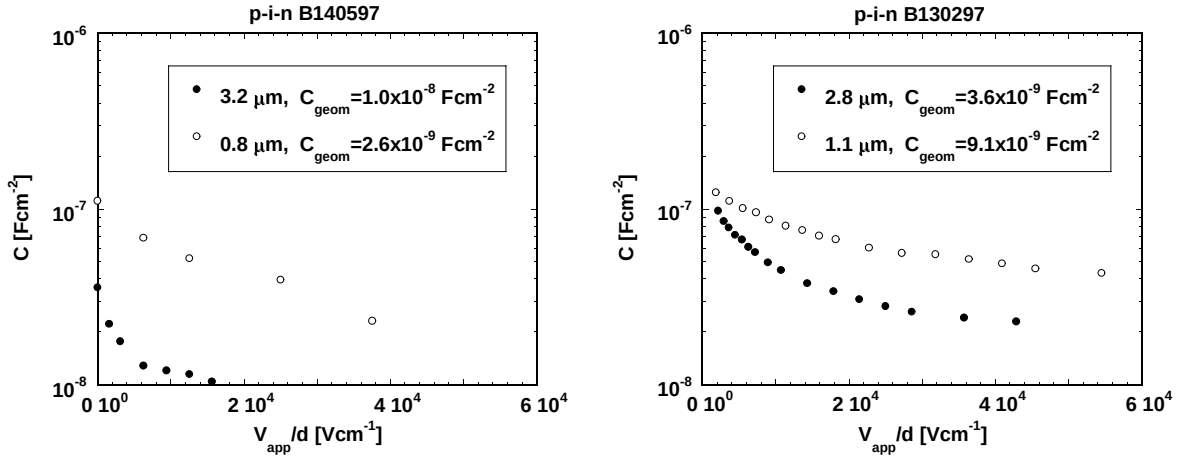

Figure 6: Capacitance as a function of applied voltage for two thickness pairs of μc-Si:H p-i-n cells. Note that, for most cases, the capacitance is much larger than the geometrical one (as indicated in the inset).

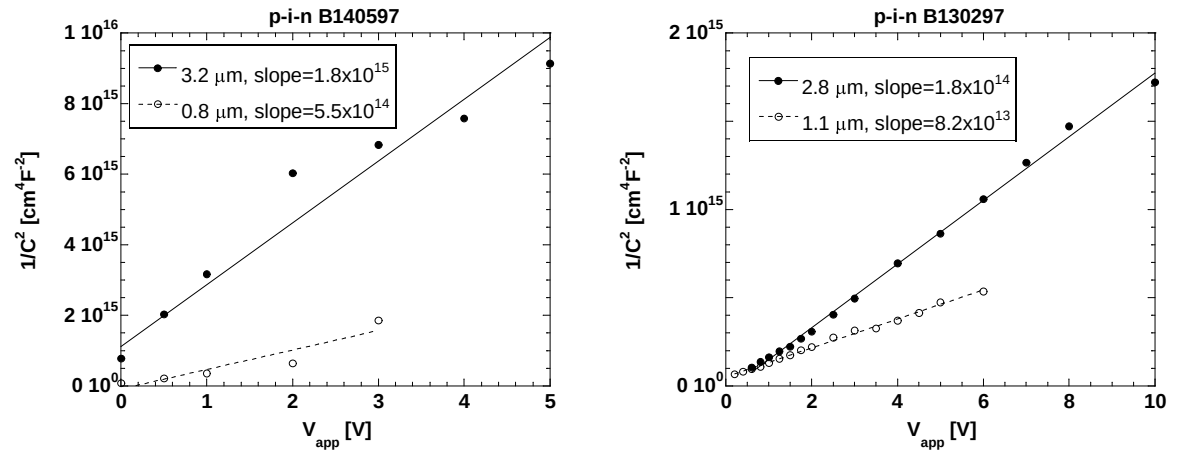

Figure 5: Inverse of the square of the capacitance as a function of applied voltage for two thickness pairs of μc-Si:H p-i-n diodes.

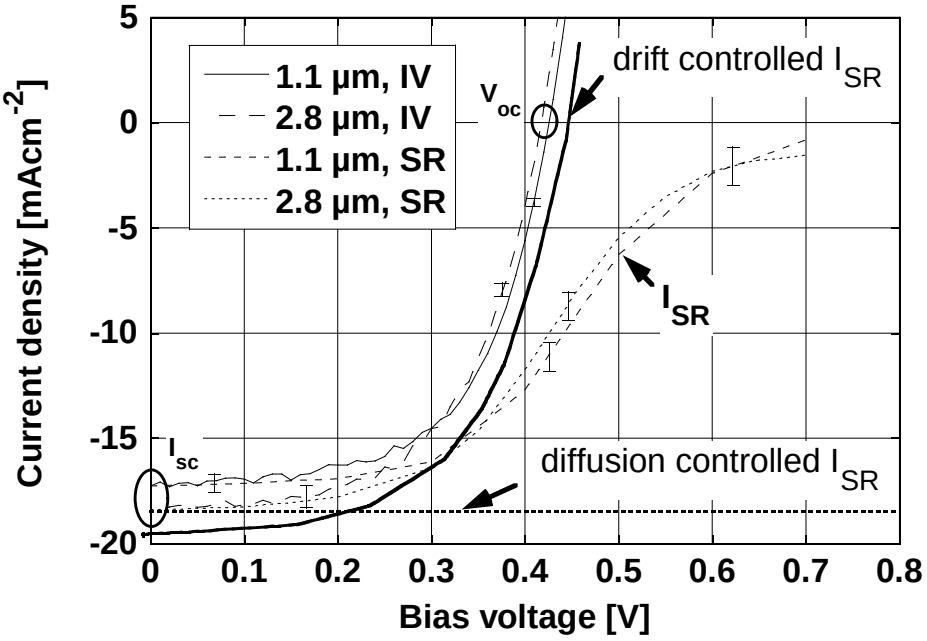

Figure 7: Current density for 2 µc-Si:H p-i-n diodes (1.1 and 2.8 µm thick) as a function of bias voltage measured directly under AM1.5 100 mWcm^{-2} illumination (IV) as well as current density I_{SR} calculated from spectral response measurements (SR). Note that I_{SR} was found to be independent of the illumination level. The typical behaviour of I_{SR} measured on an a-Si:H p-i-n diode (drift-controlled device) and on a c-Si p-n (diffusion-controlled device) is also indicated.

rather a set of grain boundaries which are connected both in series and in parallel. An increase of the slope refelects here an increase in the number of grain boundaries, given by the increase of the i-layer thickness.

From charge collection and the capacitance measurements, we can draw the conclusion that the built-in voltage V_{bi} value is given, by two approximately equal contributions: about half of V_{bi} corresponds to the voltage drops over grains and the other half of V_{bi} to the integral of the field within the grains; field contribution from the p-i, resp. n-i interfaces seem negligeable.

From the fact that internal field values in the centre of the i-layer of thick µc-Si:H p-i-n diodes are larger than those found in p-i-n a-Si:H, one may prematurely conclude that µc-Si:H diodes are also field-controlled. However, such picture would be misleading. As observed in the I(V) characteristics of 2 µc-Si:H p-i-n diodes with different thicknesses (cf. Fig. 7), the thickness of the i-layer influences only the short-current whereas the open circuit voltage V_{oc} remains almost unchanged. Furthermore, the current $I_{SR}(V)$ calculated from the voltage dependent spectral measurement (by integrating the product of an AM1.5 illumination spectra with the spectral response measured at a given bias voltage V) appears also almost independent of thickness, and therefore of the field. These two observations lead one to conclude that transport is diffusion-limited in µc-Si:H p-i-n cells. However, if one compares the I_{SR} curve with the typical response of a fully drift-limited device (a-Si:H p-i-n diode) or that of a fully-diffusion limited device (c-Si p-n diode) indicated in Fig. 7, one can see that we are, in fact, in an intermediate situation. The simplest model that could account for all above observations is the following: transport in µc-Si:H p-i-n device is diffusion-limited in the grains whereas it is drift limited at grain boundaries. This model can explain why a positive spectral response is observed (photo-generated carriers are still collected) at high values of forward bias voltage: collection is suppressed only when the field at the grain boundaries is cancelled by the externally applied field, since transport within the grains is diffusion-controlled (and field independent).

CONCLUSIONS

μc-Si:H p-i-n diodes exhibit very high values of the electric field E(x) in the i-layer (compared to a-Si:H). Capacitance measurements lead to the conclusion that the field is not uniformly distributed, but is concentrated in the region of grain boundaries. In contrast with a-Si:H, the contribution of the field located near the doped layer to the built-in voltage is small. A rather disturbing dichotomy is found between the high collection efficiency (observed in the TOF experiment) and both the field independence of the spectral response and of the I(V) characteristics. In order to reconcile these two observations, one has to take into account the non-homogeneous nature of μc-Si:H (small crystallites imbedded in an amorphous tissue). As a simple practical model one may suppose that we have drift-controlled at grain boundaries, while transport inside the grains is diffusion-controlled.

More work is definitely needed to improve the comprehension of these devices. In this context, simulation work would also be helpful, but need as a prerequisite more insight in the exact influence of grain boundaries on the electric transport.

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